

Reference heavy flavour cross sections in pp collisions at $\sqrt{s} = 2.76$ TeV, using a pQCD-driven \sqrt{s} -scaling of ALICE measurements at $\sqrt{s} = 7$ TeV

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We provide a reference in proton–proton collisions at the energy of the Pb–Pb 2010 run at the LHC, $\sqrt{s} = 2.76$ TeV, for the p_t -differential production cross section of D^0 , D^+ , and D^{*+} mesons in $|y| < 0.5$, of electrons from heavy flavour decays in $|y| < 0.9$, and of muons from heavy flavour decays in $2.5 < y < 4$. The reference is obtained by applying a pQCD-driven scaling (based on the FONLL calculation) to ALICE preliminary data at $\sqrt{s} = 7$ TeV. In order to validate the procedure, we scale the D meson cross section to $\sqrt{s} = 1.96$ TeV and compare to the corresponding measurements from the CDF experiment.

I. INTRODUCTION

In 2010, the Large Hadron Collider (LHC) delivered large samples of proton–proton (pp) collisions at $\sqrt{s} = 7$ TeV and of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. A pp reference at $\sqrt{s} = 2.76$ TeV is required, in order to compare heavy flavour production in Pb–Pb and pp collisions via the nuclear modification factor of the p_t distributions

$$R_{AA}(p_t) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_t}{d\sigma_{pp}/dp_t}. \quad (1)$$

Here, $\langle T_{AA} \rangle$ is the average value of the nuclear overlap function in a given Pb–Pb centrality class, N_{AA} is the production yield per event of the considered particle in that class, and σ_{pp} is its production cross section in pp collisions at the same energy.

In this note, we show that state-of-the-art perturbative QCD calculations provide an accurate guidance for extrapolating to lower energy the p_t -differential cross sections measured at 7 TeV. It was already shown [1], using the MNR [2] NLO pQCD calculations at the energies $\sqrt{s} = 5.5$ and 14 TeV, that, despite the large spread for the cross section at a given energy with different values of the heavy quark masses and factorization/renormalization scales, the ratio of the cross sections at the two energies is much less dependent on the choice of the calculation parameters. We now use the Fixed Order Next-to-Leading Log (FONLL) calculations [3], and apply the resulting scaling factor to preliminary ALICE cross section measurements at 7 TeV: D mesons (D^0 , D^+ , and D^{*+}) at mid-rapidity and single leptons (electrons at mid-rapidity and muons at forward rapidity) from charm and beauty hadron decays. In order to validate the procedure, we scale the D meson cross sections to $\sqrt{s} = 1.96$ TeV and compare to the corresponding measurements from the CDF experiment [4].

After reporting the ALICE heavy flavour cross section measurements at $\sqrt{s} = 7$ TeV (section II), we describe (section III) the procedure adopted for the energy scaling, and (section IV) the scaling factors and resulting cross sections at 2.76 TeV.

II. ALICE HEAVY-FLAVOUR PRODUCTION MEASUREMENTS AT $\sqrt{s} = 7$ TeV

Here we briefly present the ALICE measurements at $\sqrt{s} = 7$ TeV that will be used for the scaling.

The preliminary results on the D^0 , D^+ , and D^{*+} cross sections at $\sqrt{s} = 7$ TeV, measured at central rapidity ($|y| < 0.5$) using the decay channels $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$, are shown in Fig. 1. The data are compared to pQCD predictions based on the FONLL [3, 5] and GM-VFNS [6] calculations. These results are described in [7, 8]. Let us recall that these measurements correspond to the direct charm production, as they were corrected for the B-mesons feed-down contribution.

Fig. 2 shows the preliminary cross section of electrons from heavy flavour decays for pp collisions at $\sqrt{s} = 7$ TeV and the corresponding prediction from the FONLL pQCD calculation [3, 5]. A reasonable agreement between data and model calculation is observed. The analysis procedure is discussed in [10].

The inclusive p_t and η differential cross section of muons from heavy flavour decays, in the rapidity range $2.5 < y < 4$, in pp collisions at $\sqrt{s} = 7$ TeV is displayed in Fig. 3 [13], along with the corresponding FONLL prediction [3, 5].

III. ENERGY SCALING PROCEDURE

In order to scale the ALICE 7 TeV cross-sections to a given energy we consider the scaling factors provided by different theoretical calculations. The FONLL [3, 5] driven scaling is set as our reference scaling and is evaluated considering the different sets of scales (factorization scale μ_F , renormalization scale μ_R) and quark masses (m_c and m_b). We consider the standard parameter variations that are used to evaluate the theoretical uncertainty on the charm and beauty production cross sections (see e.g. [11, 12]):

- $0.5 < \mu_F/\mu_0 < 2$ (central value: 1);
- $0.5 < \mu_R/\mu_0 < 2$ (central value: 1);
- with the constraint $0.5 < \mu_F/\mu_R < 2$;
- $1.3 < m_c < 1.7$ GeV (central value: 1.5 GeV) and $4.5 < m_b < 5.0$ GeV (central value: 4.75 GeV);

where $\mu_0 = \sqrt{m_Q^2 + p_{t,Q}^2} = m_{t,Q}$.

The procedure to compute the FONLL scaling factor from 7 TeV to an energy of α TeV is:

1. Rebin the FONLL predictions for $\sigma(\alpha)$ and $\sigma(7)$ for the different sets of scales (μ_F , μ_R), and quark masses (m_c and m_b) according to the ALICE 7 TeV p_t binning for each observable.

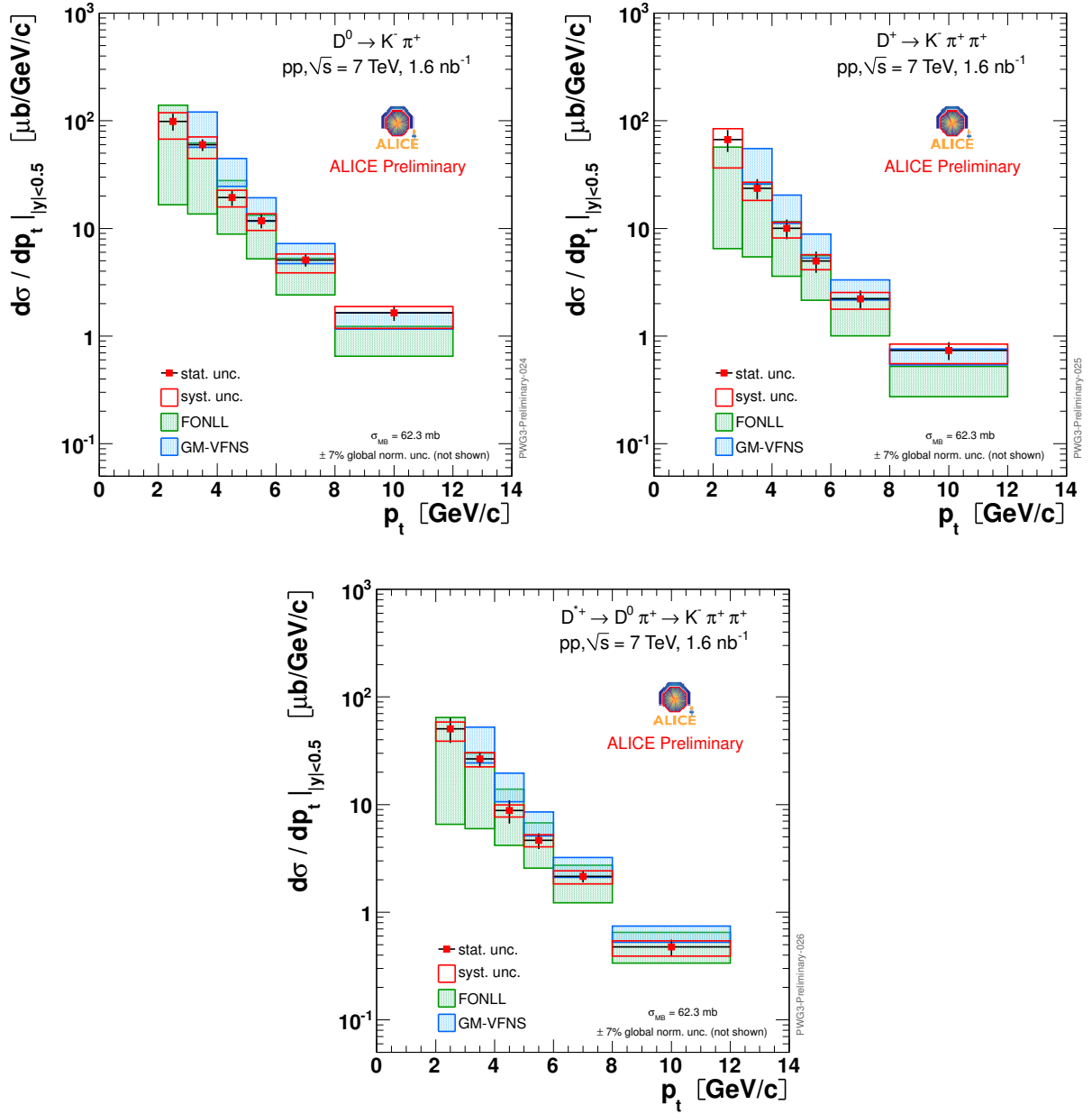


FIG. 1: ALICE D^0 , D^+ , and D^{*+} p_t differential preliminary cross sections in $|y| < 0.5$ at $\sqrt{s} = 7 \text{ TeV}$ [7]. The FONLL [3, 5] and GM-VFNS [6] predictions are compared to the data.

2. Estimate the FONLL $\sigma(\alpha)/\sigma(7)$ ratio per observable¹ considering that:

- The central value is the ratio of the central predictions at both energies and
- its uncertainty is defined by the envelope (spread) of the ratio of the calculations for the different sets of parameters. Note that for a given quark flavour we can consider that the theoretical calculation parameters are correlated (equal) at different energies. However, we do not assume they are equal for charm and beauty.

¹ This means that for single leptons this is the ratio of charm + bottom contributions.

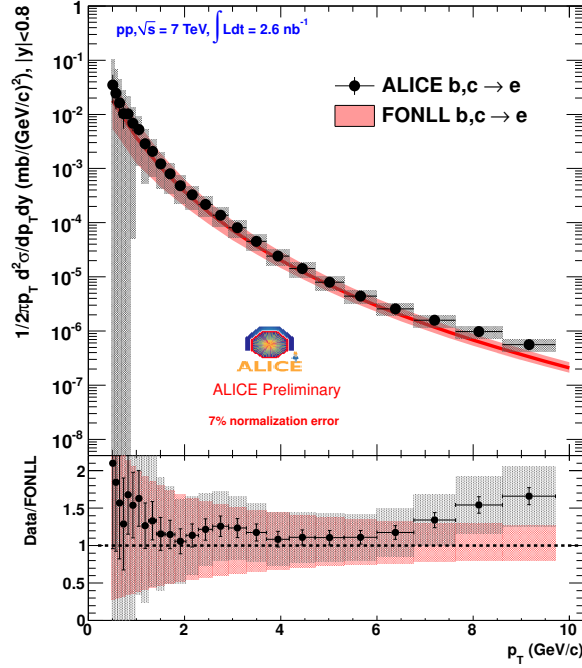


FIG. 2: ALICE heavy flavour decay electron p_T differential production cross section for pp collisions at $\sqrt{s} = 7$ TeV [10]. The FONLL pQCD calculation [3, 5] is compared to the data.

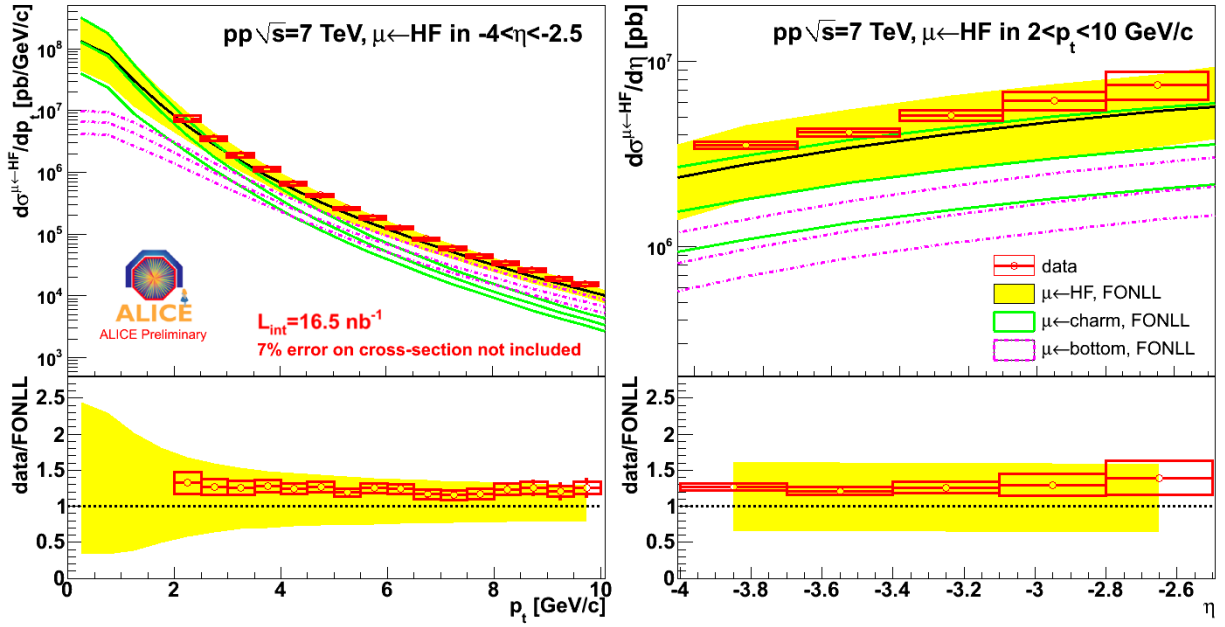


FIG. 3: ALICE p_T and η differential production cross section of muons from heavy flavour decays, in $2.5 < y < 4$, in pp collisions at $\sqrt{s} = 7$ TeV (symbols) [13]. The results are compared to FONLL predictions [3, 5].

3. Multiply the ALICE 7 TeV cross-sections by the FONLL $\sigma(\alpha)/\sigma(7)$ binned ratio.
4. Propagate the uncertainties:

- on the FONLL ratios,
- on the uncertainties of the 7 TeV measurement,
- combine these uncertainties.

The considered cross-checks of the scaling procedure are :

1. Interpolate to Tevatron energy ($p\bar{p}$ at $\sqrt{s} = 1.96$ TeV) to compare to the D meson measurements by the CDF Collaboration [4];
2. Compare the scaling factor from FONLL to that obtained from other (Fixed Order) pQCD calculations (NLO MNR [2], GM-VFNS [6]).

IV. RESULTS

A. D mesons

1. Scaling factor to $\sqrt{s} = 2.76$ TeV

The FONLL scaling factors for D^0 , D^+ , and D^{*+} were calculated as described in the previous section and are shown in Figs. 4, 5, and 6 (left-hand panels) together with their respective relative uncertainties (right-hand panels). The scaling factor obtained with the different sets of scales are drawn with solid lines, while the resulting global scaling is depicted by a yellow filled band. The central value of the scaling is obtained with $\mu_F/\mu_0 = \mu_R/\mu_0 = 1$. The values of the scales for the other sets are reported in the legend ($\mu_F/\mu_0, \mu_R/\mu_0$). We can observe that the scaling factor depends mainly on the value of the factorization scale, with almost no dependence on the renormalization scale. This is due to the fact that, for the same heavy quark p_t , different Bjorken x ranges are probed at 2.76 and at 7 TeV, and changing the factorization scale affects the x dependence of the parton distribution functions (PDFs). The scaling factor does not depend on the value used for the charm quark mass in the calculation, as shown in Fig. 7 (right) using the MNR NLO calculation. The scaling has a large p_t dependence in the low p_t region, where it varies from a factor of ≈ 0.8 at $p_t \approx 1$ GeV/c to ≈ 0.4 at $p_t \approx 5$ GeV/c, while at higher p_t the variation is less pronounced. The average scaling factor calculated for the D^0 , D^+ , and D^{*+} mesons is very similar, while some small variations can be observed on the uncertainty bands.

2. Influence of the theoretical calculation: MNR and GM-VFNS vs FONLL

The FONLL direct charm scaling has been tested by comparing the calculation to the one obtained with the MNR [2] and GM-VFNS [6] calculations.

a. MNR calculation: The MNR scaling factor for the different sets of scales is shown in Fig. 7 (left). Fig. 7 (right) shows that the influence of varying the charm quark mass from 1.3 to 1.7 is negligible. The comparison of the MNR and FONLL calculations for D^0 mesons (Fig. 8) demonstrates that, as expected, the scaling factors agree with each other, and that the uncertainties are larger for the MNR case. Therefore, from now on we will drop the MNR case for this exercise.

b. GM-VFNS calculation: We obtain the GM-VFNS scaling factor considering that the three calculation parameters (the renormalization scale, the factorization scale for initial state singularities and the factorization scale for final state singularities) do not depend on the value of \sqrt{s} , as for the FONLL case, with the difference that the latter considers only the factorization and renormalization scales. The D^0 meson scaling to 2.76 TeV is shown in Fig. 9, where the calculation parameters are varied within 1/2 (h), 1 and 2 times the standard parameters. The spread of the ratio evaluated for the different parameters indicate the scaling uncertainties.

The comparison of the D^0 FONLL and GM-VFNS scalings is shown in Fig. 10 for different p_t binnings. The agreement of the scaling central values and their uncertainties for the considered p_t bins is striking. We can then conclude that there is no need to do all the scalings both with GM-VFNS and FONLL calculations since their energy evolution (and uncertainties) are in agreement.

3. Comparison to CDF measurements in $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV

In this section, we show the comparison of the CDF [4] and the ALICE measurements scaled to 1.96 TeV.

We evaluated the scaling factor from 7 TeV to 1.96 TeV with the FONLL calculations. These estimates were used to scale the D^0 , D^+ , and D^{*+} cross sections measured by ALICE to 1.96 TeV. Figures 11, 12, and 13 present the comparison of these scalings

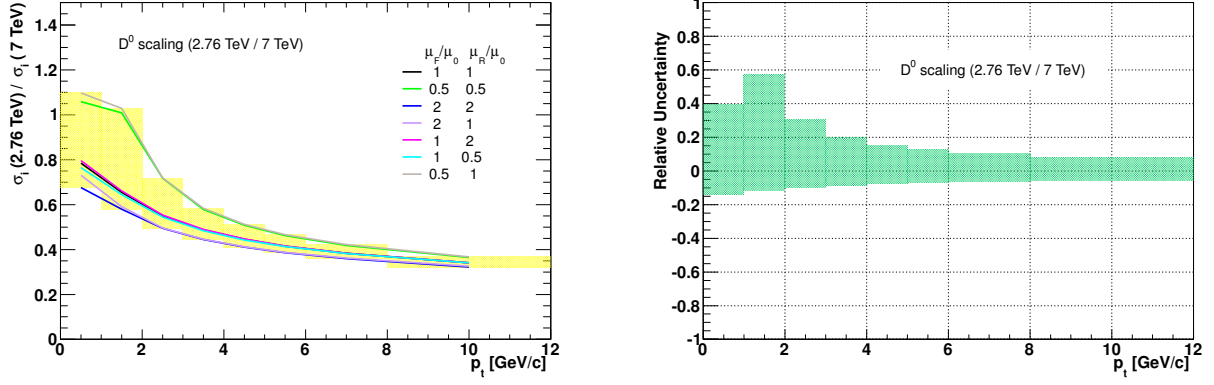


FIG. 4: D^0 FONLL scaling to 2.76 TeV from 7 TeV (7 TeV data binning).

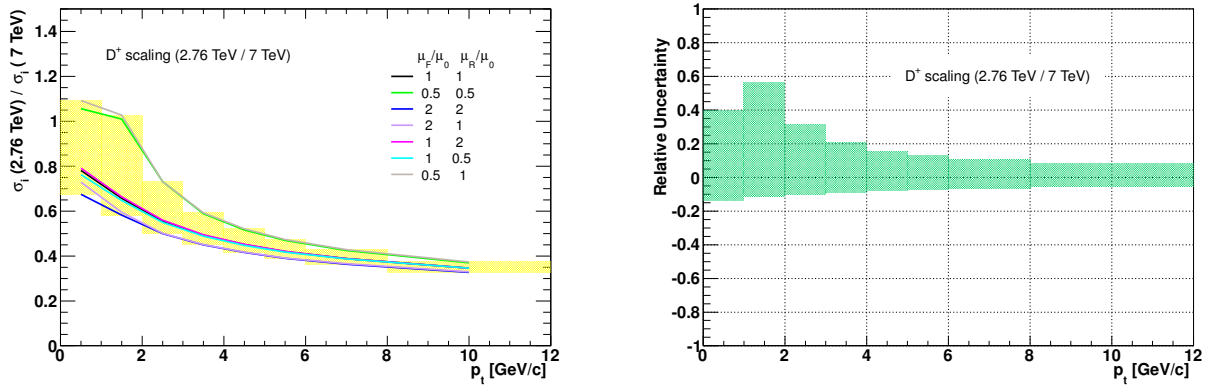


FIG. 5: D^+ FONLL scaling to 2.76 TeV from 7 TeV (7 TeV data binning).

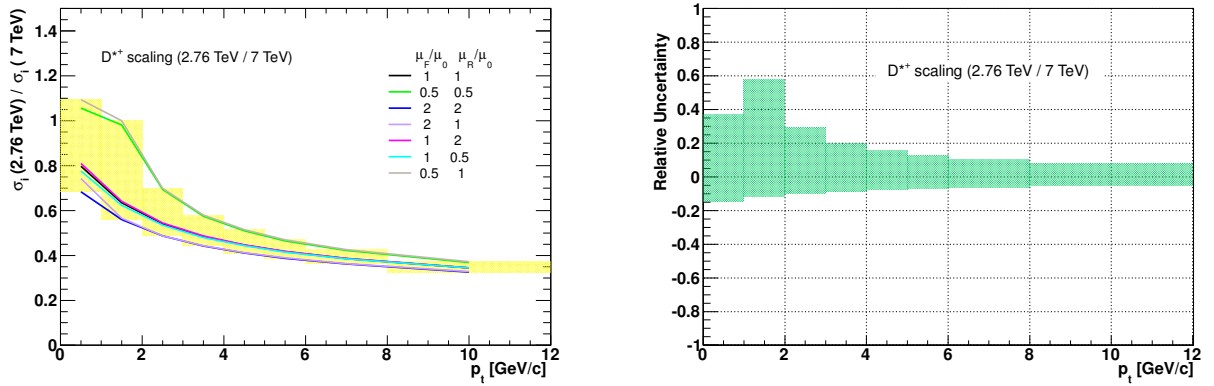


FIG. 6: D^{*+} FONLL scaling to 2.76 TeV from 7 TeV (7 TeV data binning).

and the CDF measurements². The ratio of the CDF / ALICE points is also shown (right-hand panels). The yellow (orange) bands

² Here the CDF cross sections have been rebinned to match the ALICE 7 TeV preliminary measurements binning.

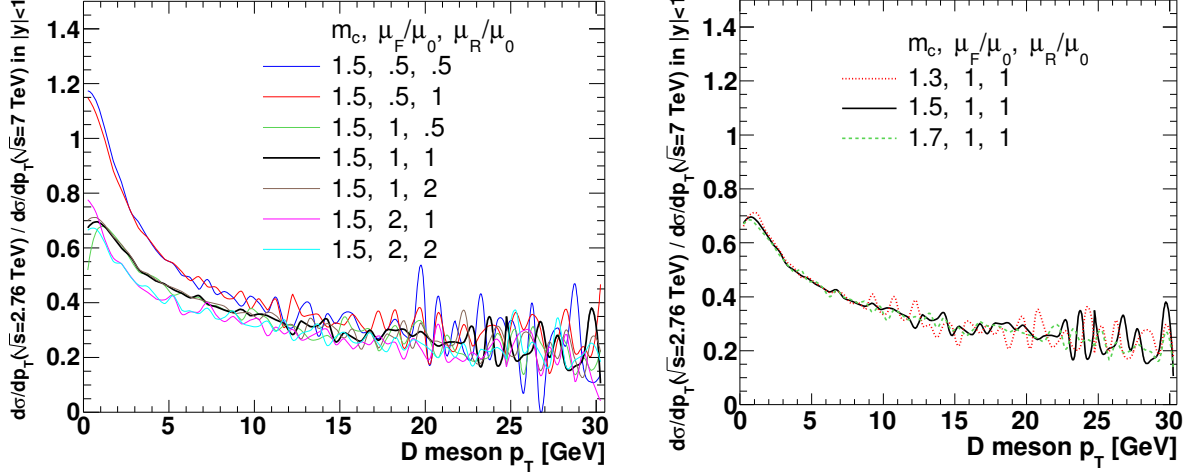


FIG. 7: D^0 MNR scaling to 2.76 TeV from 7 TeV (fine binning): scales dependence (left) and charm quark mass dependence (right).

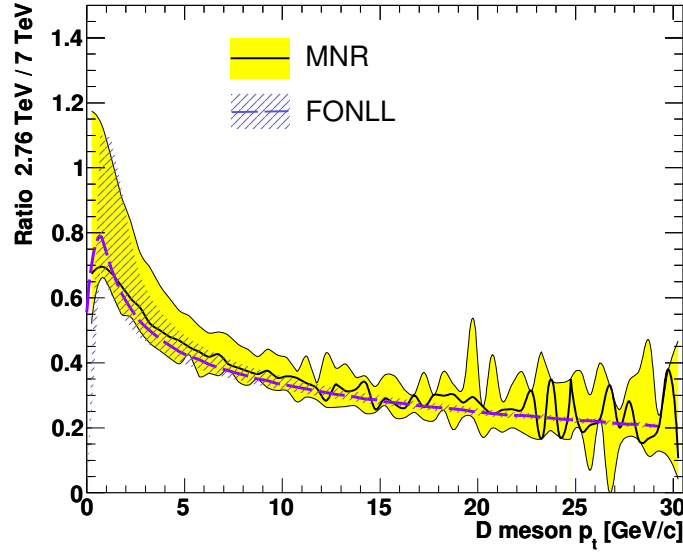


FIG. 8: D^0 MNR scaling to 2.76 TeV from 7 TeV (yellow band) compared to the FONLL scaling (purple hatched band).

describe the maximum (conservative) uncertainty on this ratio, considering that the CDF and ALICE scaled uncertainties are uncorrelated (correlated), i.e. considering the ratios of the upper-CDF to lower-ALICE (upper-CDF to upper-ALICE) and vice versa. Overall, these ratios are compatible with unity (within somewhat large uncertainties), demonstrating that the scaling procedure is reliable. We note that, for the D^{*+} case, although compatible with 1 within 1.2 sigma, the ratio is centred at 1.5: rather than to an anomaly of the scaling, which is practically the same for all D mesons, this could be related to the observation that ratio D^0/D^{*+} measured by ALICE at 7 TeV is larger than that measured by CDF at 1.96 TeV [8].

4. Results at 2.76 TeV and relative uncertainties

Finally, we can scale the ALICE D^0 , D^+ and D^{*+} measurements at 7 TeV to 2.76 TeV considering the FONLL scaling factors evaluated in section IV A 1. The scaled cross sections are presented in Fig. 14 for D^0 (top-left), D^+ (top-right) and D^{*+} (bottom).

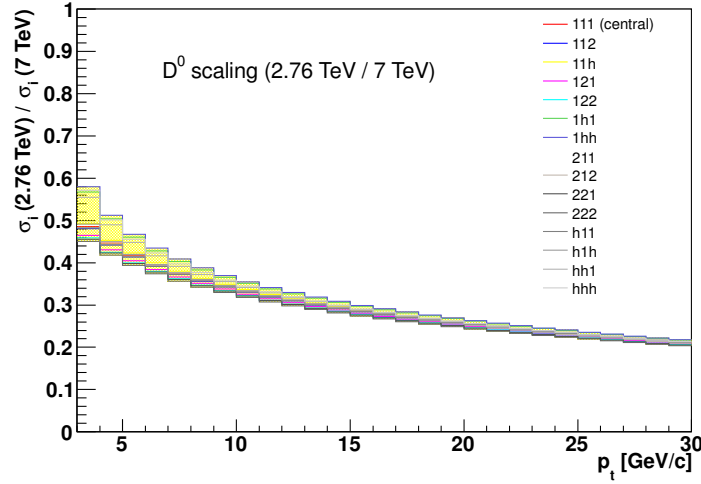


FIG. 9: D^0 GM-VFNS scaling to 2.76 TeV from 7 TeV considering that the scales are correlated vs energy. The yellow band represents the global scaling and its uncertainty. The values of the renormalization scale, the factorization scale for initial state singularities and the factorization scale for final state singularities are reported in the legend.

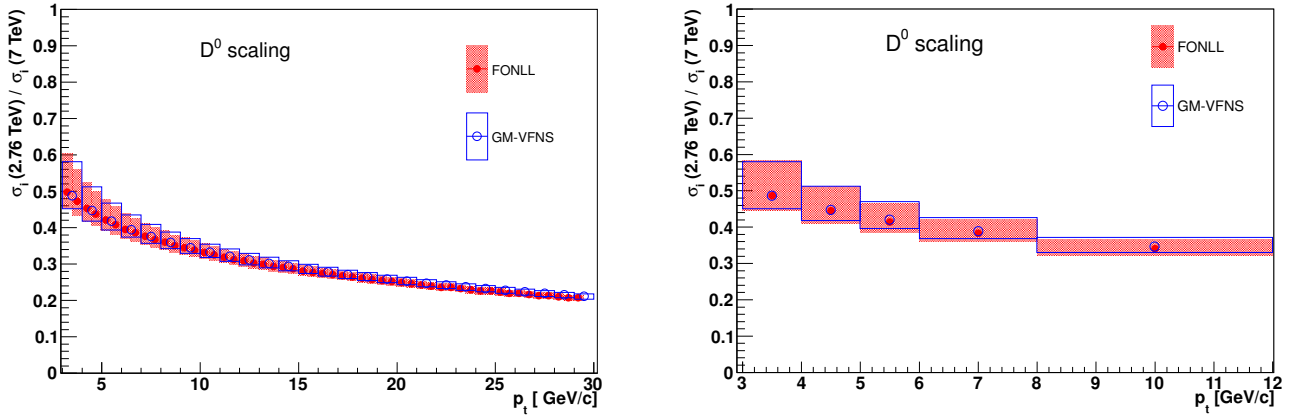


FIG. 10: Comparison of D^0 GM-VFNS and FONLL scaling to 2.76 TeV from 7 TeV with fine (left) and 7 TeV preliminary cross section binning (right).

The influence of the 7 TeV data systematics and of the FONLL interpolation systematics on the global scaled systematics is also depicted, showing the relatively small contribution of the FONLL scaling uncertainties.

B. Heavy flavour decay electrons in $|y| < 0.8$

The FONLL scaling factor from $\sqrt{s} = 7$ TeV to $\sqrt{s} = 2.76$ TeV is calculated for electrons from charm and beauty decays using the approach described in section III. For all charm related calculations shown in this section we assume that neutral D mesons contribute 70% to the total electron yield and the remaining 30% originate from charged D meson decays.

In the case of electrons from heavy flavour decays an additional complication arises from the fact that the relative contributions from charm and beauty decays change as function of p_t and are not known a priori. Therefore, it is crucial to compare the scaling for electrons from charm decays and beauty decays separately before evaluating a combined scaling function. This comparison is shown in the left panel of Fig. 15 for the default choices of quark masses, parton distribution function, and scales μ_R and μ_F . The scaling factors for electrons from charm and beauty decays are almost the same except for the region of low transverse

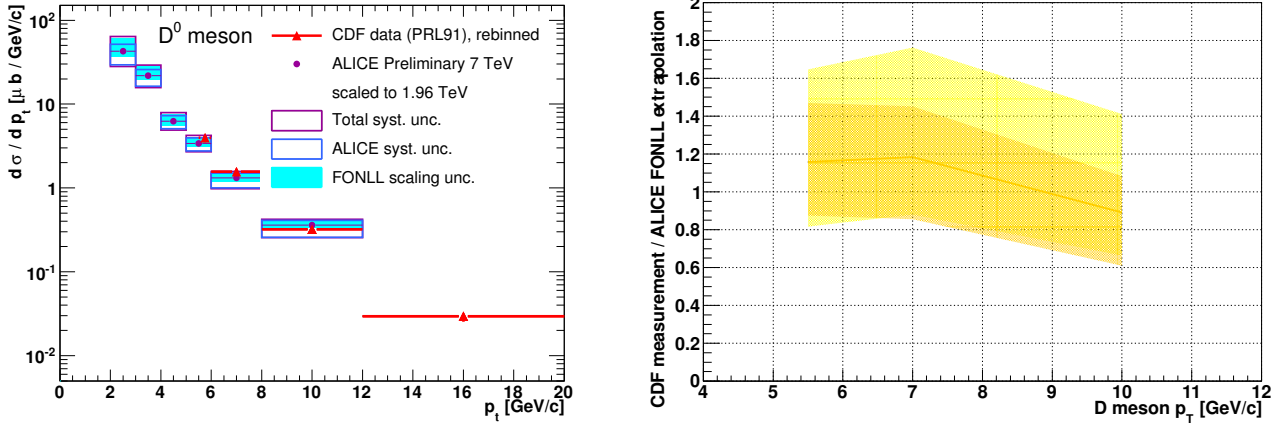


FIG. 11: Left: Comparison of D^0 ALICE 7 TeV measurements scaled to 1.96 TeV with the CDF measurements. Right: ratio of these two. The yellow (orange) band describes the maximum (conservative) uncertainty on the ratio, considering that the CDF and ALICE scaled uncertainties are uncorrelated (correlated). Note that the first CDF data point, $5.5 < p_t < 6 \text{ GeV}/c$, is compared to the ALICE data point for $5 < p_t < 6 \text{ GeV}/c$.

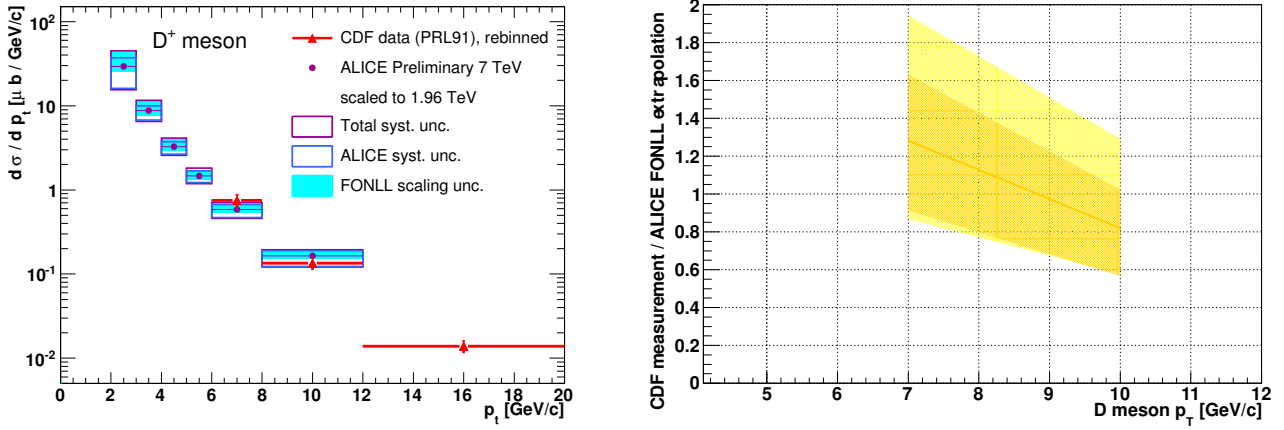


FIG. 12: Same as in Fig. 11, for D^+ .

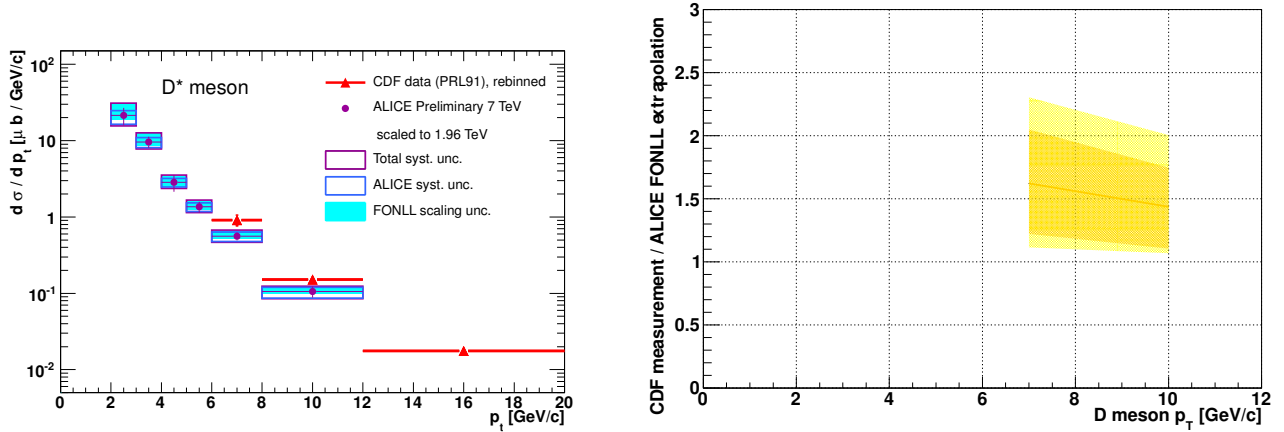


FIG. 13: Same as in Fig. 11, for D^{*+} .

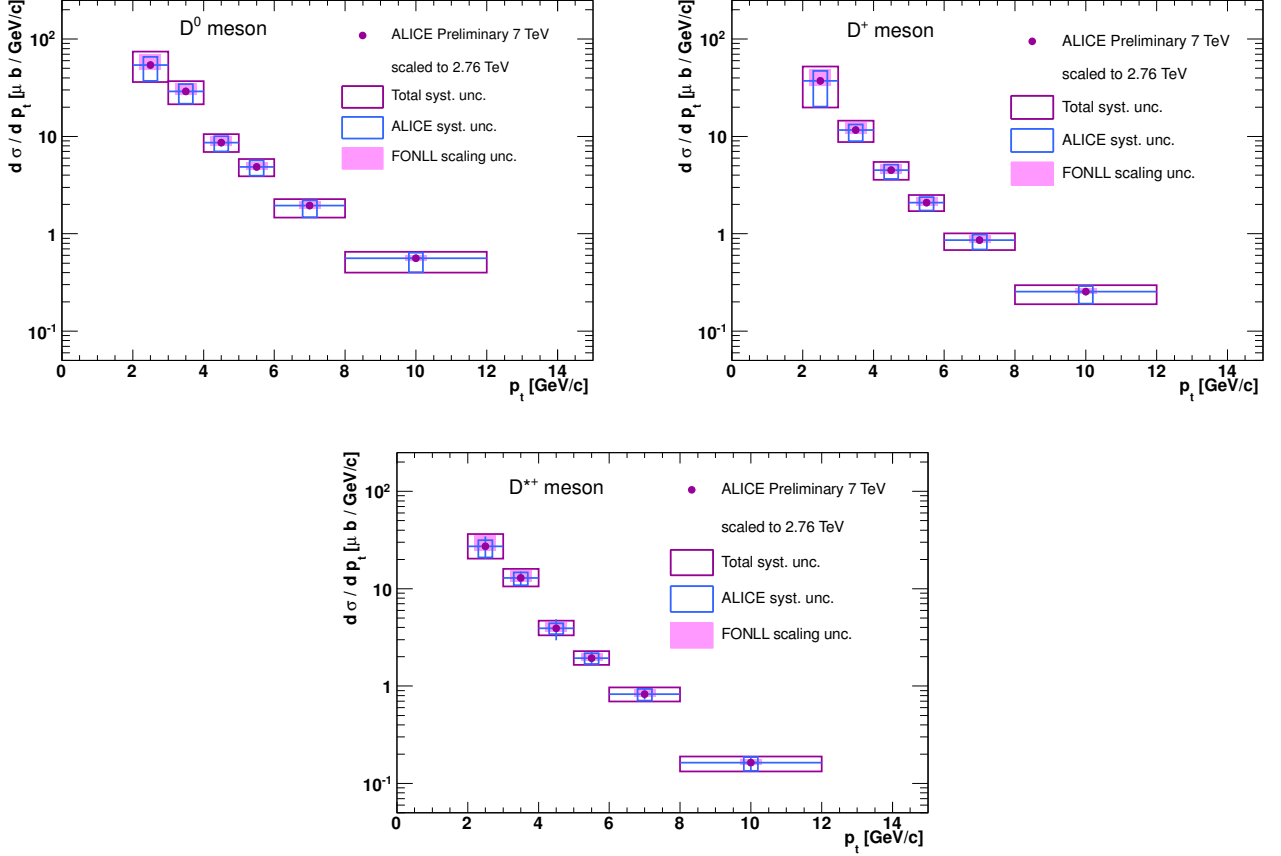


FIG. 14: D^0 (top-left), D^+ (top-right), and D^{*+} (bottom) ALICE 7 TeV measurement scaling to 2.76 TeV. The purple points and boxes represent the interpolated cross section and its global systematics. The blue empty (magenta filled) boxes indicate the 7 TeV measurement (FONLL interpolation) contribution to the systematics.

momenta ($p_t < 2$ GeV/c), where the relative contribution from beauty decays to the total heavy flavour decay electron yield is tiny.

The agreement of the charm and beauty decay electron scaling factors as observed in FONLL justifies to calculate one combined scaling factor for heavy flavour decay electrons as the ratio of the sum of charm and beauty decay electron cross sections at 2.76 TeV relative to the sum at 7 TeV. This combined scaling factor is shown in the right panel of Fig. 15 for the default FONLL parameters.

In the following, we discuss the uncertainties of the combined heavy flavour decay electron scaling factor due to the uncertainties of the FONLL parameters, *i.e.* the uncertainties of the quark masses and the scale parameters μ_R and μ_F .

The dependence of the scaling factor on the quark masses turns out to be negligible as demonstrated in Fig. 16. Here, we consider quark masses of $m_c = 1.5 \pm 0.2$ GeV and $m_b = 4.75 \pm 0.25$ GeV.

As for D mesons, the dependence of the heavy flavour decay electron scaling factor on the choice of the FONLL scale parameters is addressed in Figs. 17 and 18. In addition to the FONLL default scales $\mu_R = \mu_F = \mu_0$, we calculate the scaling factor for the scale values $0.5\mu_0$ and $2\mu_0$.

First, we assume that the scales are the same for charm and beauty. The resulting heavy flavour electron scaling factors are shown in Fig. 17. The spread of the calculations with different scaling factors is of order 10% or less for an electron p_t larger than 2 GeV/c.

However, it can not be excluded that the scale parameters vary independently for charm and beauty. To quantify the uncertainty due to that possibility we show in Fig. 18 the heavy flavour electron scaling factors one can calculate with individual choices for the scale parameters for charm and beauty in FONLL. The resulting spread of these calculations is within the envelope of the calculations for which the same scale parameters have been used for charm and beauty.

Figure 19 shows the cross section of electrons from heavy flavour decays measured by ALICE at $\sqrt{s} = 7$ TeV and the result of the scaling to 2.76 TeV.

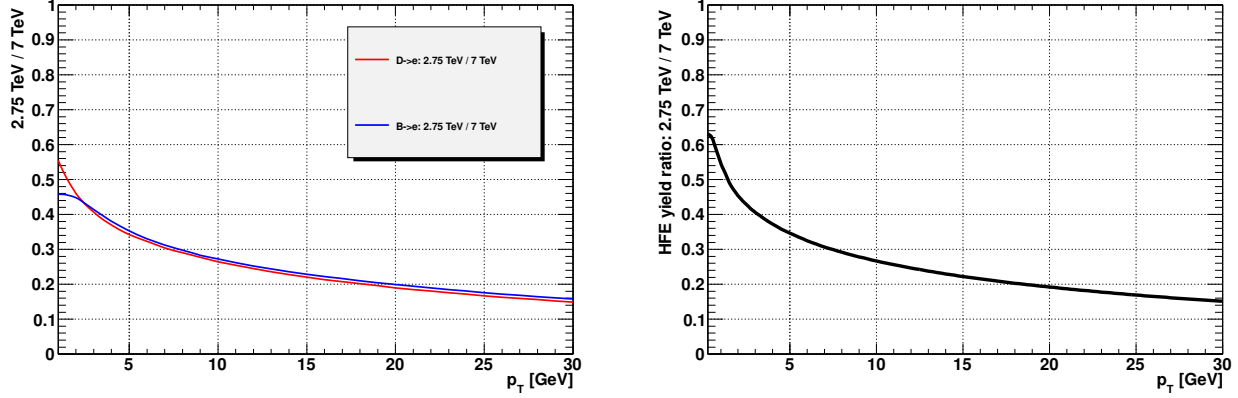


FIG. 15: FONLL scaling factor from 7 TeV to 2.76 TeV for electrons from charm and beauty decays, respectively (left panel). Combined FONLL scaling factor for electron from heavy flavour decays (right panel).

C. Heavy flavour decay muons in $2.5 < y < 4$

The FONLL scaling factor that will be applied to the p_T -differential cross section of muons from heavy flavour decay measured in pp collisions at $\sqrt{s} = 7$ TeV, in order to obtain the reference cross section at $\sqrt{s} = 2.76$ TeV, was determined according to the procedure described in section III. The only difference with respect to the case of electrons (section IV B) is that two different rapidity ranges are used for the FONLL calculations: $|y| < 0.8$ for electrons and $2.5 < y < 4$ for muons. Figure 20 shows the scaling factor obtained by combining different sets of c and b quark masses and assuming that quark masses are unchanged at 2.76 TeV and 7 TeV. The scaling factor depends strongly on p_T , in particular in the low p_T range ($p_T < 2$ GeV/c). It decreases from about 0.5 to 0.2 in the p_T range 0–6 GeV/c and tends to saturate (Fig. 20, left panel). The relative scaling factor, which gives the relative uncertainty, is depicted in the right panel of Fig. 20. Changes in the quark masses introduce a systematic uncertainty less than 5% for $p_T < 2$ GeV/c, which can be neglected at higher p_T (range of interest for the measurement of the cross section of muons from heavy flavour decay).

As in the other cases, it was assumed that the pQCD scales do not change with \sqrt{s} . As for electrons at central rapidity, the influence of the pQCD scales variation on the FONLL scaling factor was investigated in two cases: a) same scales for charm and beauty (correlated scales, colour lines in Fig. 21); b) different scales for charm and beauty (uncorrelated scales, black lines in Fig. 21). Very similar results are obtained with correlated or uncorrelated scales for charm and beauty. At low muon p_T (< 2 GeV/c) the uncertainty on the scaling factor reaches about 40%, while in the $p_T > 2$ GeV/c range it is below 10%, independently of p_T .

In summary, the FONLL scaling factor as a function of p_T obtained for different sets of quark masses (blue boxes) and pQCD scales (red boxes), as just discussed, is shown in Fig. 22 (left panel). The relative scaling factor is also shown in the right panel of the figure. For the systematic uncertainty from energy scaling, we consider the spread of the ratio obtained with the different sets of parameters (yellow band).

Figure 23 shows the cross section of muons from heavy flavour decays obtained by scaling to $\sqrt{s} = 2.76$ TeV the ALICE measurement at 7 TeV shown in Fig. 3.

V. CONCLUSIONS

We have presented a procedure to define the \sqrt{s} -scaling factors for heavy flavour production cross sections in pp collisions at LHC energies. The scaling is based on perturbative QCD calculations, as implemented in the FONLL scheme, which described reasonably well heavy flavour production as measured at the Tevatron and at the LHC. For D mesons and heavy flavour decay leptons, the scaling uncertainty from 7 to 2.76 TeV is of about 40% for $p_T < 2$ GeV/c and < 1 GeV/c respectively, and it decreases towards larger momenta, reaching a level below 10%. For D mesons, the scaling was verified by comparing the scaled ALICE 7 TeV measurement to data by the CDF experiment at 1.96 TeV.

By applying the scaling to ALICE preliminary measurements at 7 TeV for D^0 , D^+ , D^{*+} , electrons and muons from heavy flavour decay, we have provided reference cross sections in pp collisions at 2.76 TeV.

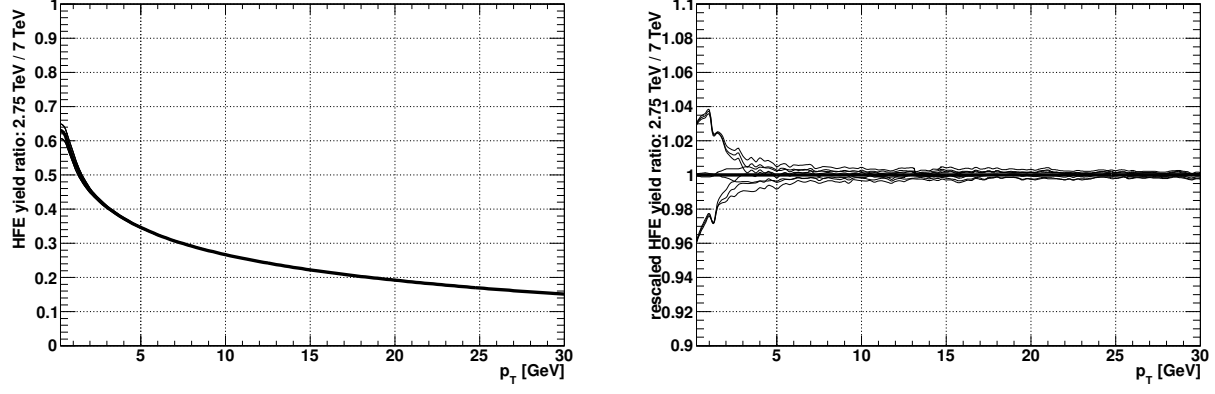


FIG. 16: FONLL scaling factor from 7 TeV to 2.76 TeV for electrons from heavy flavour decays with different values for the bare quark masses (left panel). Variation of scaling factors obtained with different quark masses relative to the scaling factor calculated with the default quark masses (right panel).

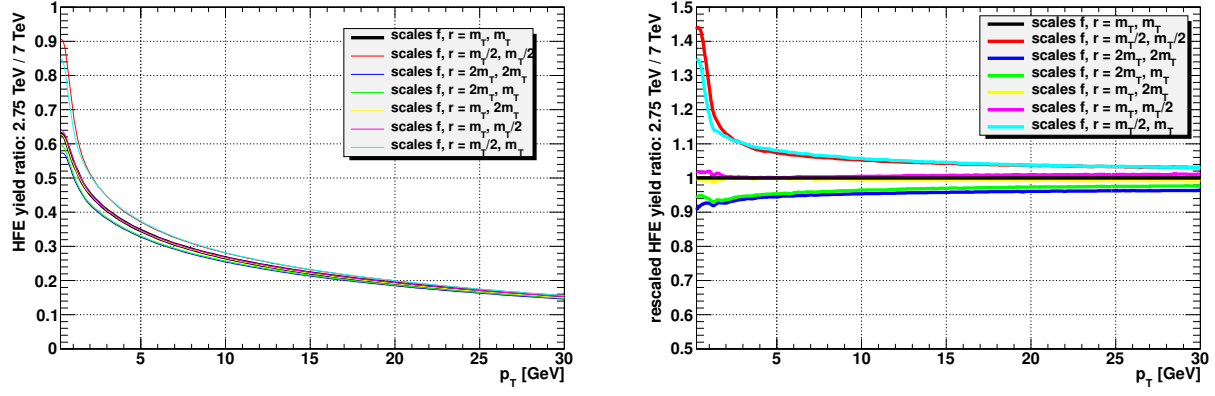


FIG. 17: FONLL scaling factor from 7 TeV to 2.76 TeV for electrons from heavy flavour decays with different values for the scale parameters μ_R and μ_F , which are chosen to be the same for charm and beauty (left panel). Variation of scaling factors obtained with different scale parameters relative to the scaling factor calculated with the default scale parameters (right panel).

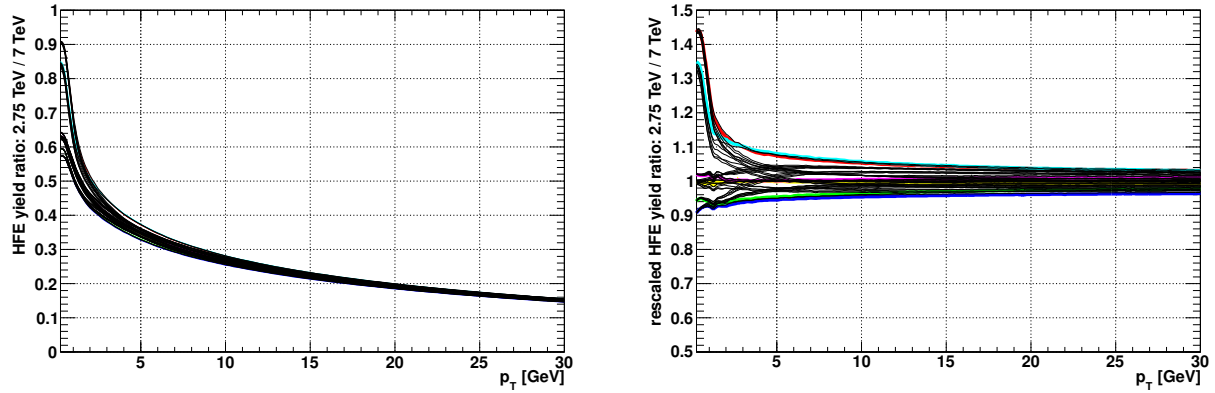


FIG. 18: FONLL scaling factor from 7 TeV to 2.76 TeV for electrons from heavy flavour decays with different values for the scale parameters μ_R and μ_F , where the scale parameters are allowed to vary independently for charm and beauty (left panel). Variation of scaling factors obtained with different scale parameters relative to the scaling factor calculated with the default scale parameters (right panel).

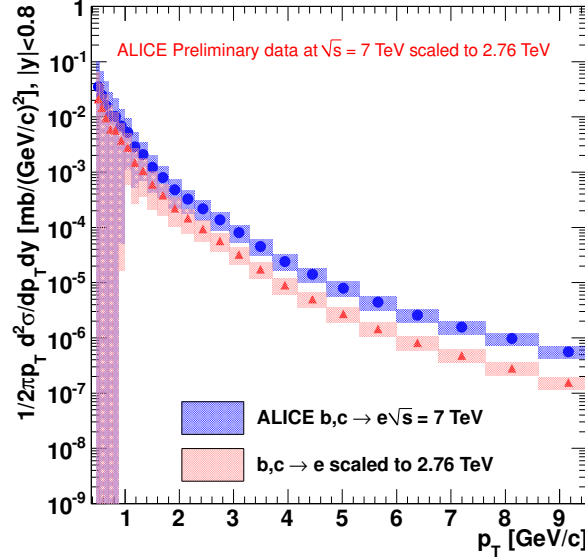


FIG. 19: Cross section of electrons from heavy flavour decays measured by ALICE at $\sqrt{s} = 7$ TeV [10] and the result of the scaling to 2.76 TeV.

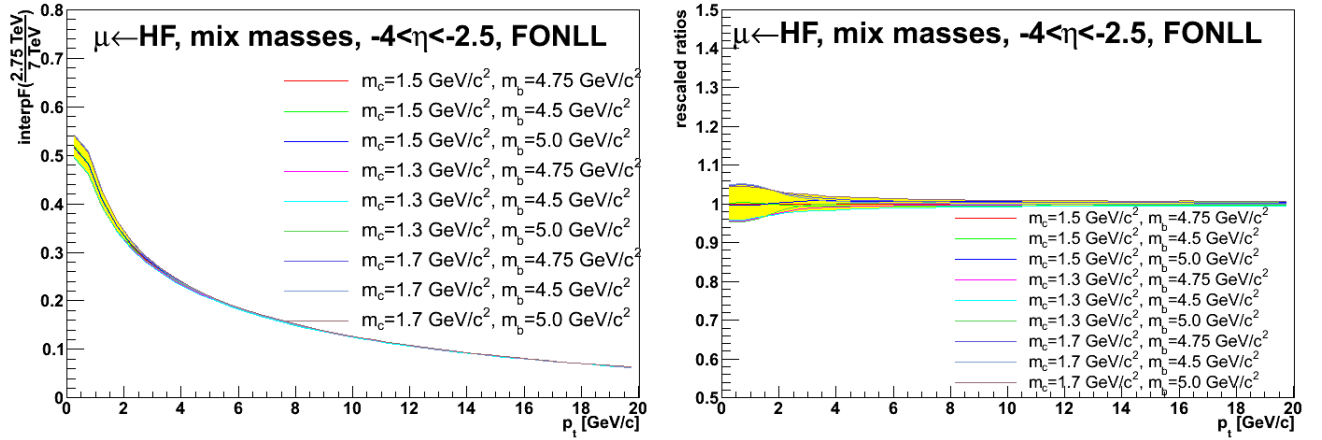


FIG. 20: Left: FONLL scaling factor from 7 TeV to 2.76 TeV for the measurement of p_T -differential cross section of muons from heavy flavour decay with different combinations of quark masses indicated on the figure; right: corresponding relative systematic uncertainty.

Acknowledgments

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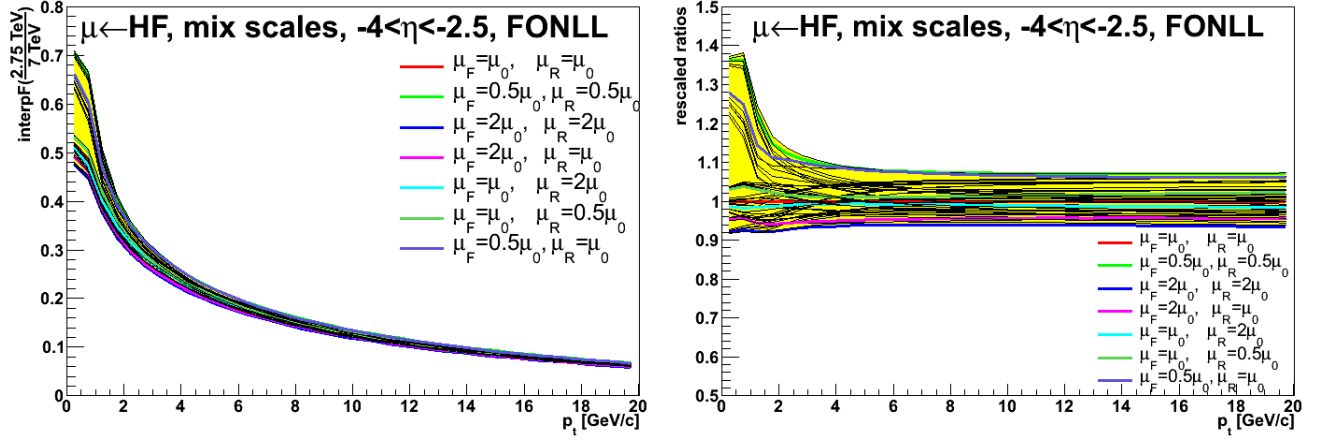


FIG. 21: Left: FONLL scaling factor from 7 TeV to 2.76 TeV for the measurement of p_t differential cross section of muons from heavy flavour decay with different combinations of QCD scales as indicated on the figure; right: corresponding relative systematic uncertainty. See the text for more detail.

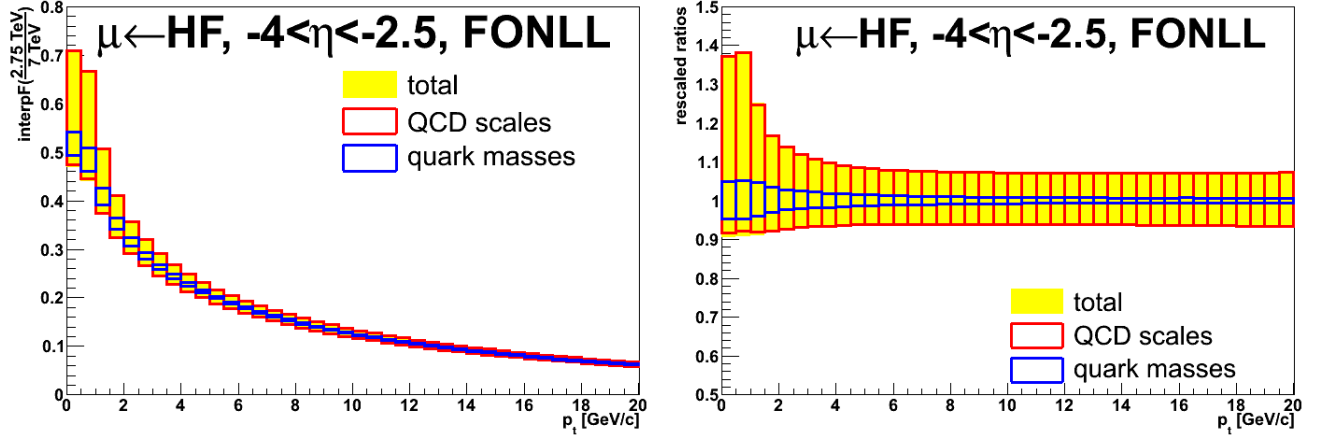


FIG. 22: Left: FONLL scaling factor from 7 TeV to 2.76 TeV for the measurement of p_t differential cross section of muons from heavy flavour decay with different combinations of QCD scales (red boxes) and quark masses (blue boxes). The yellow band is the total systematic uncertainty; right: corresponding relative systematic uncertainty.

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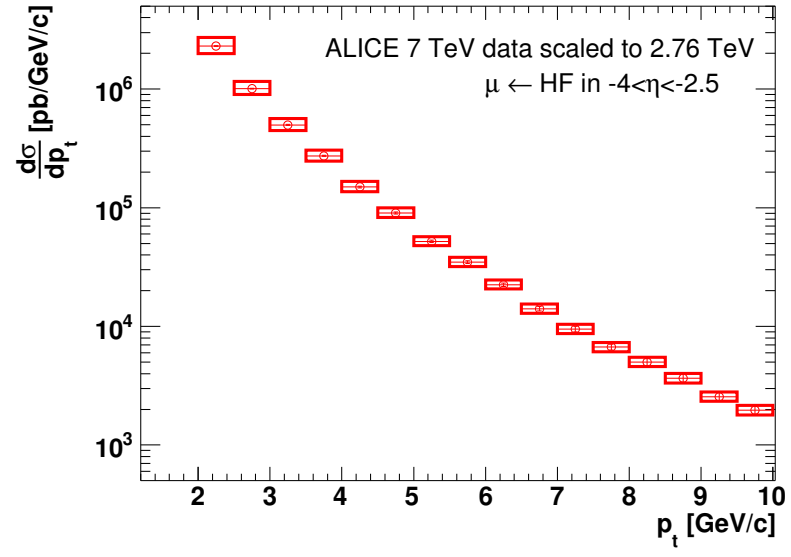


FIG. 23: p_t differential cross section of muons from heavy flavour decays obtained by scaling to $\sqrt{s} = 2.76$ TeV the ALICE measurement at 7 TeV [13].